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Abstract. We present a novel chirped pulse amplification method which combines optical parametric amplification and laser amplification. We have demonstrated this hybrid CPA concept with a combination of beta-barium borate and Ti:sapphire. High-efficiency, multi-terawatt compatible amplification is achieved without gain narrowing and without electro-optic modulators using a simple commercial pump laser.

1. Introduction

Optical parametric chirped pulse amplification (OPCPA) [1, 2] is an attractive short pulse amplification technology because of its simplicity, broad bandwidth and large gain. Furthermore, OPCPA does not intrinsically produce pre-pulses and does not require electro-optic switching to either select a single pulse from an oscillator pulse train prior to multipass amplification or to inject/eject a pulse from a regenerative amplifier. Finally, the absence of quantum defect in OPCPA allows scaling to high average power. The major drawback of OPCPA, however, is pump conversion efficiency. The spatio-temporal evolution and relatively long pulse width of commercial Q-switched lasers limits conversion. The highest OPCPA extraction efficiency reported to date from a system pumped by a commercial Q-switched Nd:YAG laser is 6%. [3] It is expensive and complicated to produce an ideal pump pulse with a top hat spatial and temporal profile. However, a unique feature of optical parametric amplification that distinguishes it from amplification in laser gain media is the fact that no pump absorption and energy storage occurs in the optical parametric amplifier (OPA). If a small temporal slice of the pump pulse is converted in OPCPA, essentially all of the remaining pump energy is available after OPCPA to pump another laser amplifier. Since a laser amplifier acts as an integrator of the residual pump energy, it is essentially insensitive to the temporal modulation of the pump pulse. In this way, hybrid chirped pulse amplification (HCPA) combines a high-gain amplifier stage based on OPCPA with a high-efficiency amplifier stage based on laser amplification. Pump-to-signal conversion efficiencies of >50% or 90% of the maximum theoretical quantum efficiency have been demonstrated from chirped-pulse, Ti:sapphire-based laser amplifiers pumped by commercial Nd:YAG lasers [4].

The HCPA scheme can be applied to a number of nonlinear materials/laser gain media combinations (see Table 1). The requirements that dictate the selection of materials in HCPA are the existence of pump bands at pump laser wavelength,

existence of laser transition at the desired operating wavelength, and the broad bandwidth of selected OPA nonlinear crystal at the operating wavelength.

Table 1. Some potential combinations of OPA nonlinear crystals and laser amplifiers for use in HCPA

Desired wavelength	Pump laser	OPA nonlinear crystal	Laser amplifier
100-400 nm	527 or 628 nm	SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam)	Ti:sapphire
200-400 nm	527 or 628 nm	SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam)	Dye laser
300-400 nm	527 or 628 nm	SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam)	Dye laser
400-400 nm	527 or 628 nm	SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam)	Dye laser
500-400 nm	527 or 628 nm	SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam)	Dye laser
600-400 nm	527 or 628 nm	SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam)	Dye laser
700-400 nm	527 or 628 nm	SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam)	Dye laser
800-400 nm	527 or 628 nm	SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam)	Dye laser
900-400 nm	527 or 628 nm	SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam)	Dye laser
1000-400 nm	527 or 628 nm	SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam) or SHG (external beam) or SHG (internal beam)	Dye laser

2. Experimental demonstration of HCPA at 800 nm

We have experimentally demonstrated HCPA at 800 nm. Our system is presented in Figure 1. A mode-locked Ti:sapphire oscillator produces 26.5-nm FWHM pulses centered near 820 nm, which are stretched to a duration of 600 ps. The resulting 0.5-nJ pulses are used to seed the OPCA preamplifier, consisting of a 20-mm and a 15-mm BBO crystal. Noncollinear OPCA is pumped by a single 225-mJ pump pulse from a commercial frequency-doubled, Q-switched Nd:YAG pump laser operating with single longitudinal mode. We obtained up to 3-mJ amplified pulses from the OPCA preamplifier, with a gain of 6×10^4 .

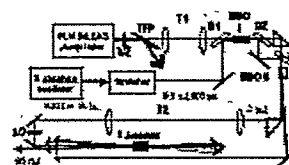


Fig. 1. Experimental setup. TFP-thin film polarizer, T-telescope, D-dichroic.

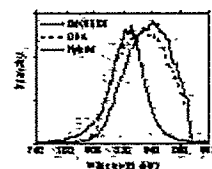


Fig. 2. Seed and amplified signal spectra

After pump conversion to signal and idler in the OPCA, and after some losses on unoptimized coatings of dichroic beamplitters, the remaining pump energy

available is 195 mJ. This energy is relay-imaged onto a Ti:sapphire crystal bow-tie amplifier, which had a single pass absorption of 90%. The output of this amplifier was 65 mJ, or 37% conversion efficiency of the absorbed pump energy. The measured beam quality of these amplified pulses was $M^2(\text{horizontal})=1.4$, and $M^2(\text{vertical})=1.7$. The measured shot-to-shot energy stability of the four-pass amplifier was 3% (1 std. deviation in 100 shots). The measured prepulse contrast level of our system is set by the total gain and was better than 10^5 .

In Figure 2 we show the measured spectra of the stretched oscillator pulse, OPCPA, and four-pass amplifier. Oscillator pulse has a FWHM bandwidth of 26.5 nm, while the spectrum of the pulses amplified in OPCPA is broadened to 49 nm FWHM as a result of nonuniform temporal saturation. After saturated amplification in Ti:sapphire, the center wavelength of the amplified pulse shifts to 840 nm. The FWHM bandwidth of the 65-mJ output was 44.5 nm. Transform-limited pulse width related to this spectrum is 30 fs.

3. Conclusions

In summary, we have demonstrated a novel hybrid architecture combining OPCPA and laser amplification, which eliminates the need for electro-optic modulators, produces gain "broadened" output capable of supporting multiterawatt pulses, and intrinsically provides high prepulse contrast. This scheme exhibits superior energetic performance when compared to a system based on OPAs alone and superior bandwidth and simplicity when compared to a system based on laser amplification alone. The demonstrated 37% absorbed energy-to-signal conversion efficiency in BBO-Ti:sapphire HCPA is highest to date in an OPA-based CPA system pumped by a tabletop commercial pump laser. Scaling of this scheme can produce >10 TW pulses using a single commercial pump laser.

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